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Changing predictability of Indian monsoon rainfall anomalies?

STEFAN HASTENRATH and LAWRENCE GREISCHAR
Department of Meteorology, University of Wisconsin–Madison, U.S.A.

Abstract. The predictability of Indian summer monsoon rainfall from pre-season circulation indices is explored from observations during 1939–91. The predictand is the all-India average of June–September precipitation NIR, and the precursors examined are the latitude position of the 500 mb ridge along 75°E in April (L), the pressure tendency April minus January at Darwin (DPT), March–April–May temperature at six stations in west central India (T6), the sea surface temperature (SST) anomaly in the northeastern Arabian Sea in May (ASM), SST anomaly in the Arabian Sea in January (ANJ), northern hemisphere temperature anomaly in January–February (NHT), and Eurasian snow cover in January (SNOW). Monsoon rainfall tends to be enhanced with a more northerly ridge position, small Darwin pressure tendency, warmer pre-season conditions, and reduced winter snow cover. However, relationships have varied considerably over the past half-century, with the strongest associations during 1950–80, and a drastic weakening in the 1980s.

Four prediction models were constructed based on stepwise multiple regression, using as predictors combinations of L, DPT, T6, ASM, and NHT, with 1939–68 as "dependent" dataset, or training period, and 1969–91 as "independent" dataset or verification period. For the 1969–80 portion of the verification period calculated and observed NIR values agreed closely, with the models explaining 74–79% of the variance. By contrast, after 1980 predictions deteriorated drastically, with the explained variance for the 1969–89 time span dropping to 25–31%. The monsoon rainfall of 1990 and 1991 turned out to be again highly predictable from models based on stepwise multiple regression and linear discriminant analysis and using as input L + DPT or L + DPT + NHT, and with this encouragement an experimental real-time forecast was issued of the 1992 monsoon rainfall.

These results underline the need for investigations into decadal-scale changes in the general circulation setting and raise concern for the continued success of seasonal forecasting.

Keywords. Climate prediction; monsoon; climatic change.

1. Introduction

Climate prediction has been a challenge to Indian meteorology for over a century (reviews in Das 1986; Hastenrath 1991). Following the Great Drought of 1877–78, H. F. Blanford issued the first seasonal forecast of Indian monsoon rainfall in 1884. The leadership of Sir Gilbert Walker, in particular, during the early decades of the 20th century, laid the foundation for the diagnostic and prognostic research by generations of Indian meteorologists. As a result of this continual work, an understanding of the general circulation mechanisms of monsoon rainfall anomalies has been reached that is exemplary for the tropics at large. This has also involved the search for ever more powerful predictors of monsoon precipitation. Thus, the associations of the Indian monsoon with the Southern Oscillation (SO) have been known since Walker's classical SO research, motivated as it was by the practical task of seasonal monsoon forecasting. Relationships with the pre-season heat-low development over southern Asia, as well as with the sea surface temperature (SST) conditions in the Indian Ocean were gradually recognized, as were the associations with the upper-air circulation, culminating in Banerjee *et al*'s (1978) discovery of the April 500 mb ridge along 75°E as cardinal predictor of Indian monsoon rainfall anomalies. As a fruit of this sustained research over a century, the long-range forecasting of Indian monsoon rainfall has attained an impressive performance in recent years (Thapliyal personal communication 1992).

The enthusiasm about the performance of long-range monsoon forecasting is dampened by the realization of long-term changes in the large-scale circulation and its implications for varying prognostic relationships between the pre-season atmosphere-ocean-land setting and the Indian summer monsoon rainfall, that appears to be taking place in the course of recent years. The purpose of the present paper is to examine the implications of such long-term circulation changes for the seasonal forecasting of Indian monsoon rainfall anomalies. Section 2 summarizes recent work on seasonal forecasting, section 3 describes the data sources used, and sections 4 to 7 address the problems of recent changes in the general circulation setting and their implications for climate prediction.

2. Background

Extensive diagnostic research has led to the recognition of numerous precursors to summer monsoon rainfall anomalies. Reference is made to Das (1986), Thapliyal (1990), Hastenrath (1988, 1991), Parthasarathy *et al* (1988), and Gowariker *et al* (1989). These precursors can be grouped into three main categories, namely:

(a) upper-air flow over India,
(b) the Southern Oscillation and large-scale pressure distribution in the global tropics, and
(c) heat low development over southern Asia and establishment of meridional pressure gradient and cross-equatorial flow over the Indian Ocean.

In the development of quantitative methods for climate prediction it is appropriate to select from this multitude of precursors a limited number of predictors, with the purpose of ensuring stability of relationships. A combination of predictors from the three aforementioned categories may serve to optimize the overall information input to the prediction method. A diversity of approaches has been used, including stepwise multiple (linear) regression, power regression, neural networking, stochastic-dynamic modeling, and linear discriminant analysis (Hastenrath and Greischar 1993; Thapliyal 1990). In general, the prediction method is to be developed from a dependent portion of the total record, the "training period," and the performance is then to be tested on the independent portion of the record, the "verification period" that has not been used in the method development. For Indian summer monsoon rainfall, the most promising predictors stem from a limited time window in the season preceding the monsoon. In previous work on the seasonal forecasting of Indian monsoon rainfall anomalies (review in Hastenrath 1991), a few index time series have been found particularly effective for their predictive potential. These are of particular interest in the present paper and they are described in context in section 3.

3. Data

Observations are here used in the form of compact index series with one value per year (figures 1 and 2). Most important is a measure of Indian summer monsoon rainfall. To that end the index NIR was adopted from Mooley and Parthasarathy (1984) and Parthasarathy *et al* (1992), being the all-India average of June–September precipitation computed from a network of 306 well-distributed and quality-controlled stations. This predictand index NIR is plotted in figure 2 H, along with the time series of the various predictors.

Turning to the predictors, various elements have been proposed in the category (a) describing the upper-air flow over India (Thapliyal 1982; Parthasarathy *et al* 1990; review in Hastenrath 1991). Of these, the latitude position of the April 500 mb ridge along 75°E, introduced by Banerjee *et al* (1978), was found the most powerful and in fact pivotal for long-range monsoon forecasting. This element, here denoted by L, is the only one from the category of upper-air precursors, used in the present study. Values from 1939 to 1980 are available from Thapliyal (1982); the series was updated for 1981–90 from published radiosoundings, as described in Hastenrath (1987); and for the later years the ridge position was determined from the upper-air analyses of the National Meteorological Center, NOAA, Washington, D.C., provided by John Janowiak. Continuity between these three sources was ensured by comparative determinations for overlapping years. A time series plot of index L is offered in figure 2A.

In the category (b) of elements describing the SO and the large-scale pressure distribution, various options appear. These include the pressure difference Tahiti minus Darwin (figure 1), say in April, an index here called SOI. Another index is the pressure

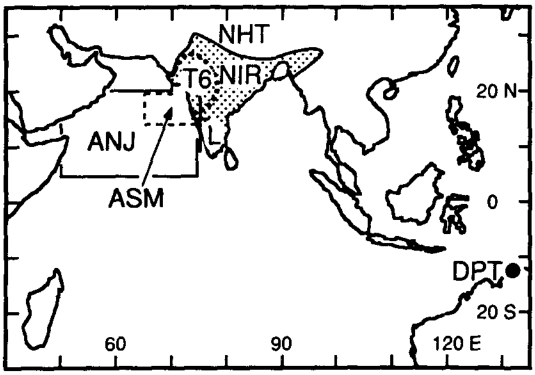

Figure 1. Orientation map showing spatial context of predictors. Dot raster indicates domain of all-India rainfall index NIR; L is April latitude position of 500 mb ridge along 75°E; DPT pressure tendency April minus January at Darwin, northern Australia; T6 March–April–May temperature at six stations in west central India; ASM May SST in northeastern Arabian Sea; ANJ January SST in Arabian Sea; NHT northern hemisphere temperature in January–February.

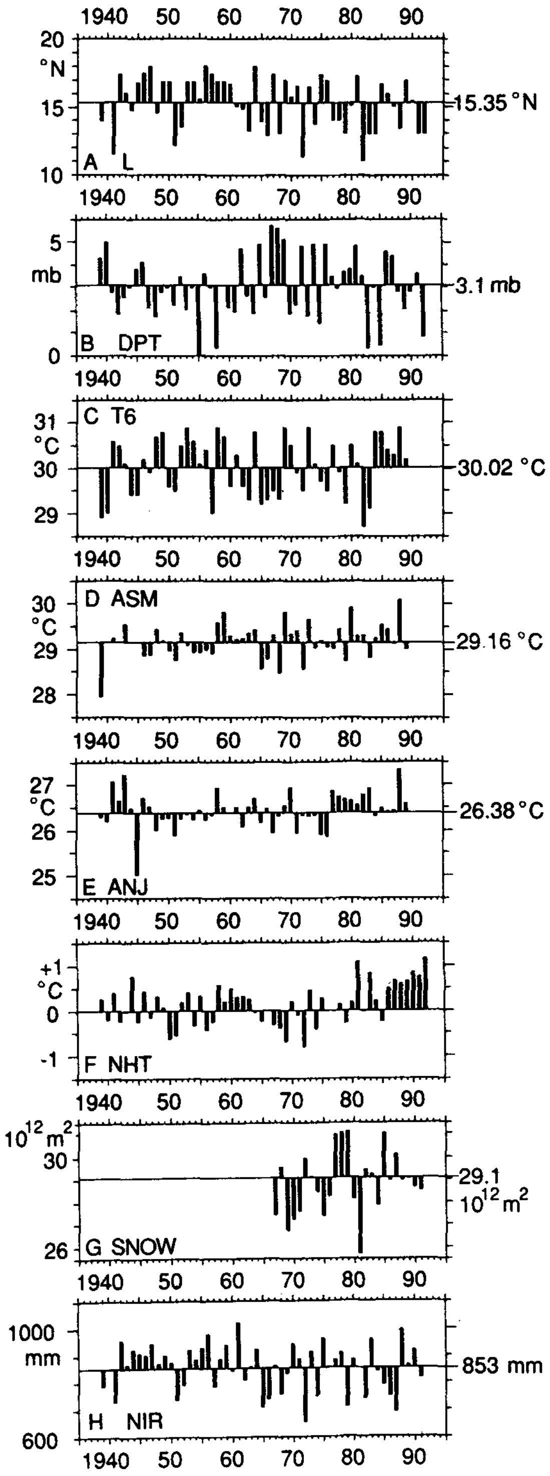

Figure 2. Time series plots of elements associated with Indian monsoon rainfall (ref. figure 1). (A) Latitude position of 500 mb ridge along 75°E in April, L; mean is 15·35°N (Thapliyal 1982; Hastenrath 1987). (B) Pressure tendency (April minus January) at Darwin, DPT; mean is 3·1 mb. (C) March–April–May temperature (°C) at stations in west central India, T6; mean is 30·02°C. (Parthasarathy *et al* 1990). (D) SST anomaly in northeastern Arabian Sea (°C) in May, ASM; mean is 29·16°C. (Bottomley *et al* 1990). (E) SST anomaly in Arabian Sea (°C) in May, ANJ; mean is 26·38°C. (Bottomley *et al* 1990) (F) Northern hemisphere temperature anomaly in January–February, NHT; (Jones *et al* 1986). (G) Eurasian snow cover in January, SNOW; mean is 29·1 × $10^{12} m^2$. (H) All-India index of summer monsoon rainfall NIR; 1979–83 mean = 853 mm per year (Mooley and Parthasarathy 1984).

at Darwin, for which Thapliyal (1990) found the combination March–April–May expedient. As proposed by Shukla and Mooley (1987), however, the pressure tendency (April minus January) at Darwin (ref. figure 1) is found to be even more effective than other information from the Darwin or Tahiti pressure series. This index, in mb, is here called DPT and is plotted in figure 2B. In a variation of this theme, Parthasarathy *et al* (1988) proposed the Bombay pressure tendency, BPT, being the difference of pressure in March–April–May minus that in December–January–February. It may be argued that BPT belongs as well to the category (c) of predictors to be considered in the following.

In the predictor category (c) pertaining to heat low development, meridional pressure gradient, and cross-equatorial flow, a considerable diversity of pre-season precursors has been proposed, and various of these are considered here. Parthasarathy *et al* (1990) presented an index of March–April–May temperature for the period 1891–1989, being the average temperature of six stations in west central India. This index in °C is here referred to as T6, and is plotted in figure 2C.

In a similar vein, we constructed two SST indices from the long-term ship observations of the "File 31" contained in Bottomley *et al* (1990). In accordance with an exploratory analysis of sensitivity and data coverage, these pertain to two different months and to two different domains of the Arabian Sea. An index ASM, in °C, represents the SST anomalies of May in the northeastern Arabian Sea (domain 15–20°N, 65–75°E; 20–25°N, 70–75°E). Another index ANJ, likewise in °C, was obtained from the SST anomalies of January in the Arabian Sea (domain 5–20°N, 50–75°E). The SST indices ASM and ANJ are plotted in figures 2D and 2E, respectively.

Furthermore belonging into this category (c) is the index NHT displayed in figure 2F. This is a measure of the northern hemisphere temperature by Jones *et al* (1986) for the years 1851–1984 and updated through 1992 by correspondence. The index NHT used here is for January–February. Verma *et al* (1985) and Prasad and Singh (1992) found this element to be closely associated with the subsequent monsoon rainfall.

Winter snow cover as a precursor of the Indian summer monsoon has been a subject of interest since the work of H. F. Blanford a century ago (review in Hastenrath 1991). Bhanu Kumar (1988a, b) has resumed this line of investigation by demonstrating that the satellite-derived January snow cover over Eurasia is negatively related to the April 500 mb ridge position along 75°E and to Indian monsoon rainfall. Satellite-derived areas of Eurasian snow cover in January during 1972–91 were obtained from David Robinson, Rutgers University. For the period 1972–86 of common record, a regression relationship was developed of Robinson's values as a function of those from Bhanu Kumar (1988a), and on this basis values conforming to Robinson's series were calculated from the numbers reported by Bhanu Kumar (1988a) from 1967 onward. A plot of the complete 1967–91 series thus obtained is included in figure 2G.

It should be noted that of the predictor indices displayed in figure 2A to 2G some could be obtained in quasi-real time more readily than others; the prospects being perhaps least for T6 and NHT. The series of SNOW (figure 2G) is as yet too short to be of prognostic interest.

4. Pre-season circulation and Indian monsoon rainfall

Figure 2 displays the inter-annual variability of Indian summer monsoon rainfall over the past half-century in the context of key pre-season circulation indices. Comparison of the various panels reveals the prevailing associations. Thus, abundant monsoon rainfall (figure 2) tends to be presaged by an anomalously far northerly position of the 500 mb ridge along 75°E in April (figure 2A), excessively warm conditions at stations in west central India (figure 2C) and in the adjacent Arabian Sea (figure 2D and 2E), as well as over the wintertime northern hemisphere continents at large (figure 2F). Furthermore, a good Indian monsoon (figure 2) tends to be preceded by a small January to April pressure rise at Darwin, Northern Australia (figure 2B).

The elements plotted in figure 2A to 2G are indicators of the pre-season large-scale circulation setting. From combinations of these indices prediction methods have been developed, as described in section 2, using for example, stepwise multiple regression. From some combinations, remarkably large predictability has been demonstrated on an independent dataset. The April 500 mb ridge along 75°E (L, figure 2A) and the (April minus January) pressure tendency at Darwin (DPT, figure 2B) were generally found to be the most powerful predictors, and L in particular is regarded as absolutely pivotal (Hastenrath 1987, 1988, 1991; Parthasarathy *et al* 1988, 1990; Gowariker *et al* 1989; Thapliyal 1990). The high performance of these predictors has mostly been demonstrated to the mid 1980s. However, in very recent experiments at seasonal prediction it was noted that the relationships of various pre-season circulation indicators with Indian summer monsoon rainfall have deteriorated. This issue is explored in the next section.

5. Long-term changes

Figure 3 exhibits eleven-year sliding correlations of NIR with various monsoon precursors introduced in section 3 and figure 2. These times series plots are of direct relevance in the choice of predictors for seasonal forecasting.

The April latitude position of the 500 mb ridge along 75°E (figure 3A) shows very large positive correlations with NIR throughout most of the record, except for a spell centered on the late 1950s and then remarkably in the 1980s.

The Darwin pressure tendency (figure 3B) is correlated negatively with NIR, but correlations were small in the early decades, and they have also decreased in the 1980s.

The March–April–May temperature at stations in west central India (figure 3C) has overall positive correlations with NIR, alhough they are small in the 1940s and again in the 1980s. The May SST in the northeastern Arabian Sea (figure 2D) varies broadly in unison with the temperature over the adjacent land (figure 2C), and accordingly their plots of eleven-year sliding correlations are similar (figure 3D and 3C), with low values in the 1940s and again in the 1980s. As a further index of pre-season temperature conditions, January SST in the northern Arabian Sea (figure 3E) likewise exhibits prevailingly positive correlations with NIR. While stronger than those of the other two aforementioned temperature indices (figure 3C and 3D) for the 1940s and 1980s, they become negative during the 1970s.

Northern hemisphere January–February temperature (figure 3F) likewise correlates positively with NIR. In similarity to the more regional temperature indices displayed

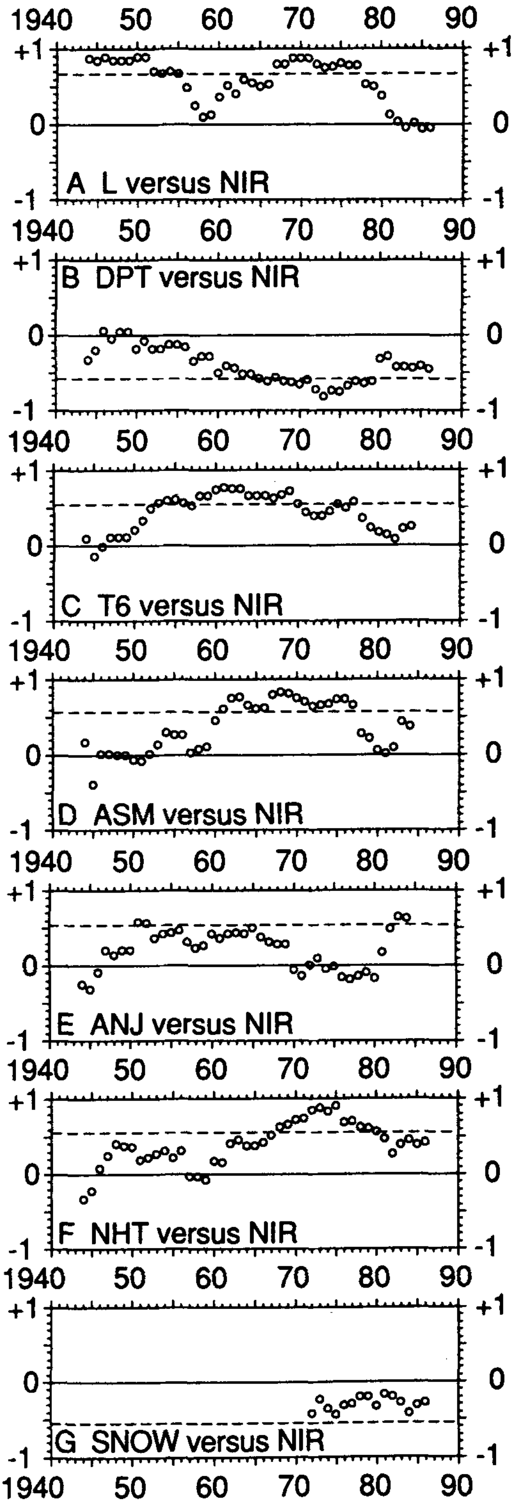

Figure 3. Eleven-year sliding correlations between Indian monsoon rainfall NIR and indicated elements. Values are plotted at the central year of 11-year interval. (A) Latitude position of 500 mb ridge along 75°E in April, L; (B) Pressure tendency (April minus January) at Darwin, DPT. (C) March–April–May temperature at six stations in west central India, T6; (D) SST anomaly in northeastern Arabian Sea in May, ASM; (E) SST anomaly in Arabian Sea in January, ANJ; (F) Northern hemisphere temperature anomaly in January–February, NHT; (G) Eurasion snow cover in January.

in figure 3C and 3D, correlations are weak in the 1950s and before, and they also have become smaller in the 1980s. The satellite-derived series of Eurasian snow cover in January (figure 2G) has maintained moderate negative correlations with NIR, but the record is as yet short.

In synthesis from the correlation series displayed in figure 3 it is noted that the relationships between pre-season circulation conditions and summer monsoon rainfall, that had persisted over several decades, have weakened drastically since the 1980s. This is interesting in relation to long-term changes in the general circulation (ref. Elliott and Angell 1987, 1988; Fu and Fletcher 1988), and also has practical implications for seasonal forecasting, an issue to be considered in the next section.

6. Prediction experiments

The application of stepwise multiple regression to climate prediction has been described in Hastenrath (1988). That account is in part repeated here. Time series of some of the circulation parameters presented in figure 2 and table 1 serve as input to the stepwise multiple regression scheme (Wilkinson 1980; Draper and Smith 1981). The general regression equations are

$$\mathrm{NIR} = b_0 + b_1 x_1 + b x_2 + \cdots b_n x_n \tag{1}$$

where NIR is the predictand, the b_i the coefficients of the regression model, the x_i the regressors (variables plotted in figure 2A–G) and n the number of regressors employed in the regression model. A significance level α is specified where the retained regression coefficients are accepted as different from zero.

A regression model is constructed on a "dependent" dataset, and the formula in the form of equation (1) thus obtained is then used in a predictive mode on an "independent" dataset. That is, the coefficients b_i are determined from a subset of the

Table 1. Summary of regression models, training period 1939–68. L, DPT, T6, ASM, and NHT are regressors as explained in caption to figure 2.

Model no.	L	DPT	T6	ASM	NHT	VAR
(A) entrance levels α and						
1	5	5	—	—	—	58
2	5	5	25	—	—	59
3	5	5	—	35	—	61
4	5	5	—	—	25	59
(B) coefficients b_i and						b_i
1	+27·5	−17·2				+482·8
2	+25·5	−11·5	+24·1			+499·5
3	+26·1	−14·3		+31·2		+499·5
4	+29·0	−13·3			+38·2	+446·9

(A) entrance level α at which regressors were accepted by model, and VAR percentage of variance explained by regression model, both in %. A dash indicates that element was not provided as input.

(B) coefficients b_i of regression models based on equation (1).

record, and these coefficients along with the observed values of x_i (elements plotted in figure 2A–G) are then entered in equation (1) to calculate the values of NIR for a portion of the record not used in determining the coefficients b_i. In an operational setting, the early portion of the record must be used to develop predictions of later years. In accordance with this practical reality, the time span 1939–68 will be used to determine the regression coefficients, while the years from 1969 onward are to be predicted.

Four statistics are used to measure the forecast skill: the correlation coefficient (CORR) between the (NIR′) and observed (NIR), the root-mean-square (RMSE), the absolute error (ABSE), and the bias (BIAS). The last three statistics are computed as follows:

$$\mathrm{RMSE} = \left[\sum^{n} (\mathrm{NIR}' - \mathrm{NIR})^2 / n \right]^{0\cdot 5}$$

$$\mathrm{ABSE} = \sum^{n} |\mathrm{NIR}' - \mathrm{NIR}| / n$$

$$\mathrm{BIAS} = \sum^{n} (\mathrm{NIR}' - \mathrm{NIR}) / n$$

where the summation extends over the n forecast years. Recognizing that the relationships between pre-season circulation indicators and monsoon rainfall deteriórated substantially in the 1980s (refs. section 5 and figure 3), the aforementioned four measures of forecast performance are here evaluated separately over the intervals 1969–80 ($n = 22$ years), 1969–89 ($n = 31$ years), and 1969–91 ($n = 33$ years), where available.

Regarding the significance testing of correlation coefficients, it should be noted that geophysical time series are not, as a rule, serially independent. Therefore, Quenouille's (1952) method was used to account for the reduction of the effective

Table 2. Forecast performance. Predictors are as defined previously.

Model no.	Forecast period	RMSE	ABSE	BIAS	CORR	VAR
1	1969–80	50	43	−6	+86**	74
	1969–89	80	63	+1	+54*	29
	1969–91	78	62	−3	+54*	29
2	1969–80	50	44	+1	+86**	74
	1969–89	83	66	+7	+50*	25
3	1969–80	48	41	−4	+87**	76
	1969–89	78	61	+4	+56*	31
4	1969–80	44	35	−10	+89**	79
	1969–89	80	63	+5	+56*	31
	1969–91	76	59	+3	+57*	32

RMSE = root-mean-square error; ABSE = absolute error; BIAS = bias; CORR = correlation coefficient between predicted and observed rainfall, in hundredths (one and two asterisks indicate significance at the 5 and 1% levels, respectively; VAR = CORR squared, in percent.

number of degrees of freedom due to persistence, based on the lag autocorrelation of the time series.

Four models were constructed using as input the elements L, DPT, ASM and NHT, for which figure 3 offered the best prospects. Model details are summarized in table 1, and results are presented in table 2 and figure 4.

Over the first two decades of the independent portion of the record, namely 1969–80, all four models exhibit strong performance, with explained variance between 74 and 79%, and moderate values of RMSE, ABSE, and BIAS (table 2). Overall, model 4 appears somewhat stronger than the other three models. The time series plots in figure 4 also show over this time interval, as well as during the 1939–68 training period, a remarkably close agreement between calculated and observed values of Indian monsoon rainfall, again for all four models.

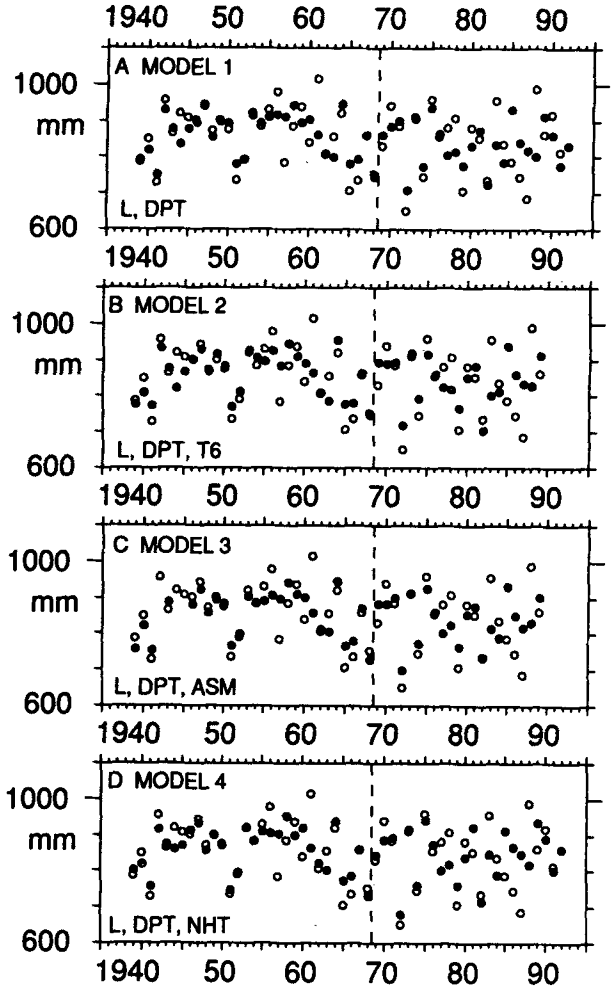

Figure 4. Time series plots from models (A) 1, (B) 2, (C) 3, and (D) 4. Indian monsoon rainfall index NIR. Solid dots denote regressed values for years up to 1968 and forecast values from 1969 onward, as separated by the vertical broken line. Open circles indicate observed NIR values.

With this background, the deterioration of forecast performance since the 1980s (figure 4 and table 2) is all the more striking. Indeed, during the past decade the spread between calculated and observed values of NIR in figure 4 has become excessive, and this is further reflected in the drastic dropoff of explained variance and increase in RMSE and ABSE for the 1969–89 and 1969–91 periods as compared to the 1969–80 interval, borne out by table 2. This should be seen in perspective with the changing relationships of individual circulation indices with Indian monsoon rainfall discussed in section 5 and illustrated in figure 3.

Complementing this work on stepwise multiple regression (SMR), limited experiments were conducted with linear discriminant analysis (LDA; Afifi and Azen 1979). Based on the SMR and LDA method development, experimental real-time forecasts of the 1992 summer monsoon rainfall were issued on 23 June 1992. Real-time input information is gratefully acknowledged as follows: L from J. Janowiak, Climate Analysis Centre of NOAA; NHT from P. D. Jones, University of East Anglia; DPT from Climate Analysis Centre, NOAA (1992). As indicated in table 1, these were used as input to models SMR1 (L + DPT) and SMR4 (L + DPT + NHT). The LDA models with the corresponding input are here called LDA1 and LDA4. By way of background, it is noted that during the 1969–80 (independent) verification series, models SMR1 and SMR4 performed very highly (ref. table 2), but not LDA1 and LDA2. In the 1980s performance was poor for all four SMR models (table 2), as well as the two LDA models. However, the 1990 and 1991 predictions from all four models agreed remarkably well with observations.

With these qualifications, the forecasts for the 1992 summer monsoon rainfall were issued as a real-time prediction experiment. Expressed in percent of the 1939–68 mean NIR of 862 mm, the values obtained for the models SMR1, SMR4, LDA1, and LDA4, were 96, 99, < 97, and 99–97%, respectively. Thus, the four models agreed in pointing to rainfall somewhat inferior to the long-term mean. The 1992 forecast values from models SMR1 and SMR4 are included in figure 4. It is intended to verify these experimental forecasts when the observed rainfall of the 1992 summer monsoon becomes available.

7. Conclusions

Seasonal forecasting of Indian monsoon rainfall anomalies has been the subject of work by the Indian meteorological community for more than a hundred years, and it has been noted (reviews in Das 1986; Hastenrath 1991; Thapliyal 1990) that this sustained effort has seemingly come to fruition in recent times. The gradual build-up of the upper-air network opened a new dimension to monsoon research, and drawing on this work Banerjee *et al* (1978) introduced the pre-season mid-tropospheric ridge over India as a new element in seasonal forecasting; it proved, in fact, to be the cardinal predictor. Results could be improved by the addition of other predictors, such as the Darwin pressure tendency, and one or the other index of pre-season temperature conditions. A multitude of other elements from diverse parts of the world are known to be associated with Indian monsoon rainfall anomalies, as described in Parthasarathy *et al* (1988), Gowariker *et al* (1989), and Thapliyal (1990). However, in order to safeguard against noise that would jeopardize the validity of the regression relationship in the independent data set, it is found effective to limit the input to very few of the most promising predictors. The performance of forecasting Indian monsoon rainfall anomalies from only two or three predictors is, in fact, exemplary for the tropics at large. As demonstrated in earlier work (review in Hastenrath 1991) and shown again in section 6, about three quarters of the inter-annual variance of monsoon rainfall is predictable, at any rate for verification periods up to about 1980. Other, logistic developments have taken place in recent years that are propitious to the application of climate prediction methods on an operational basis: communal efforts at the international level are now updating certain relevant large datasets in quasi-real time. Particularly noteworthy here are the NMC upper-air analyses that allow the assessment of the mid-tropospheric ridge position over India, the SST datasets of COADS (Woodruff *et al* 1987) and the U.K. Meteorological Office, and the monthly pressures at Darwin now regularly acquired and published in the CAC Bulletin (Climate Analysis Center, NOAA 1992).

On these grounds, it may appear that an effective synergy is evolving from the combination of the prediction methods developed and the real-time input information now at hand. However, given the growing awareness of long-term changes in circulation and climate, it was found desirable to re-assess in this study the performance of prediction methods for recent years. The more promising predictors, namely mid-tropospheric ridge position over India (L), Darwin pressure tendency (DPT), and four measures of pre-season temperature conditions (T6, ASM, ANJ, NHT), all showed strong associations with Indian monsoon rainfall (NIR) during the decades 1950–80, but not later on. This implication for individual precursor series was followed up by systematic prediction experiments using stepwise multiple regression, and various combinations of the predictors L, DPT, T6, ASM, and NHT. All prediction models had 1939–68 as training period, while the years from 1969 onward were reserved for verification on the independent data set. For the two decades 1969–80 of this independent dataset the four SMR models all explained about three quarters of the observed inter-annual variance of monsoon rainfall, a high rate by any standard and consistent with published work (review in Hastenrath 1991). However, the performance of all four SMR models deteriorated drastically after 1980, in fact so severely that the explained variance for the 1969–89 period as a whole dropped to about a fourth. The monsoon rainfall of 1990 and 1991 turned out to be again remarkably predictable, and with this encouragement an experimental real-time forecast was issued for the 1992 summer monsoon. The present findings appear important in at least two respects: in the context of global change they may merit attention as possible symptoms of transitions in the large-scale circulation setting; at the operational level they may herald new challenges to long-range forecasting.

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